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Droughts as random events in the Maya lowlands

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Abstract

Because the values of most of the parameters controlling the occurrence and severity of a drought in a given location are unknown, and no periodicity has been observed, droughts can be considered random events. Running a random number generator within the limits of the annual rainfall variability relevant to the Maya lowlands, and defining a "Lean Year", it is observed that strings of lean years occur quite frequently. Defining "Severe Drought", "Disaster", and "Catastrophe" based on the length of these strings, it is observed that a severe drought occurs on average every 32 years, a disaster occurs on average every 130 years, and a catastrophe on average every 500 years. These values fit the measured variability of the Yucatan climate, as observed in lake core sediments and in the post conquest written records. It also fits the average occurrence of "megadroughts" in the US Great Plains.

The fit between the random occurrence model and the actual, "measured" occurrence of droughts supports the notion that for all practical purposes, droughts *had been* random events in the Maya region and could not be predicted. The lack of evident periodicity could be one of the reasons why means for long-term storage of food products were not developed there. It may also have affected the relationship between the priesthood and the general populace in that region.

Since the method described here can be applied to any climatic region once the rainfall variability and the sensitivity of the local agriculture are known or can be estimated, if similar results are found they may probably have affected other regions with other ancient cultures in a similar way.

Keywords: Drought; Lowland Maya; Random; Long-term storage

1. Introduction

Tossing a coin many times is considered to be a stochastic process. In reality, each toss is a deterministic event—mechanically dependent upon the coin parameters (mass, moment of inertia, etc.), the momentum imparted to it by the thumb (linear and angular), the position of the coin relative to the thumb, etc., and several other sets of parameters. Once the values of *all* these parameters are known for *each* toss, it is possible to predict the outcome of each toss, using the appropriate simulation codes. But, generally, we do not know all the required values, these values change from one toss to the other and the means for the necessary simulation are not available on the spot. The result is that each of the tosses is considered a random event and the outcome of a series of such tosses is considered a stochastic process.

Similarly, the prediction of droughts' occurrence, location and severity using the state-of-the-art models, computer codes and computers, could be deterministic, once we had the values of all the required parameters of the problem. In order to predict droughts in a specific region, it is required to have the values of the global parameters of atmospheric circulation, heat flux balance, land/sea proportions, heat capacities of the land and sea, the time dependence of the reflectivity of the various areas, the complete set of initial conditions, etc. Additionally, the values of the local parameters are required, with sufficient resolution. Even with all the modern measuring equipment and techniques, it is not yet possible to obtain the required values of all the

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Table 1
The definitions of the various categories of drought severity

Category	Description	Possible impacts	PDI	Percent of normal precipitation	SPI
D 0	Abnormally dry	*Going into drought*: short-term dryness; slowing planting, growth of crops/pastures; fire risk above average. *Coming out of drought*: some lingering water deficit; pastures/crops not fully recovered.	−1 to −1.9	Below 75% for 3 months	−0.5 to −0.7
D 1	Moderate drought	Some damage to crops; fire risk high; streams, reservoirs or wells low; some water shortages developing or imminent; voluntary water use restrictions requested.	−2.0 to −2.9	Below 70% for 3 months	−0.8 to −1.2
D 2	Severe drought	Crop/pasture losses likely; fire risk very high; water shortages common; water restrictions imposed.	−3.0 to −3.9	Below 65% for 6 months	−1.3 to −1.5
D 3	Extreme drought	Major crop/pasture loss; extreme fire danger; widespread water shortages or restrictions.	−4.0 to −4.9	Below 60% for 6 months	−1.6 to −1.9
D 4	Exceptional drought	Exceptional and widespread crop/pasture losses; exceptional fire risk; shortages of water in reservoirs, streams, and wells, creating water emergencies.	−5.0 and less	Below 65% for 12 months	−2.0 or less

parameters, so that the predictions, using the "State of the Art" simulation codes and the most powerful computers, are bound to be only partial, primarily on the global scale, with indications of trends rather than actual values.

Ancient societies, like the Maya, had considered droughts as "acts of the gods", as indications that the gods are angry with their people about something [14]. What this something was was never very clear, and was left for the priests to find out, generally because the people themselves could not see any direct connection between their behavior, as individuals and as a group, and the occurrence of droughts, or any periodicity to their occurrence. This means that for the people of a given area, the occurrence of droughts must have been impossible to predict, i.e. they appeared as random occurrences (not for the priests, for whom there was always somebody to blame …).

Not only ancient people, but also modern day scholars have similar perception of the occurrence of droughts. In the semi-arid tropics it was observed that "Deficient rainfall years may be followed by similar years or years with excess rainfall in no predictable pattern" [20]. Such perceptions have been substantiated by testing for randomness and resulted in fitting a Poisson distribution to the drought occurrence in India over the last 200 years [16].

2. Drought definition

The simplistic, all encompassing definition of a drought is: "Drought is a condition of moisture deficit sufficient to have an adverse effect on vegetation, animals, and man over a sizable area" [22]. This definition has several derivatives, such as "Meteorological Drought", "Agricultural Drought", "Hydrologic Drought" and others [21].

The severity of a drought is complicated to define. Today, there are several *measured* indices, each relating to different aspects of a drought. The values of these indices, combined with the assessment of experts and with verification in the field, serve to define this severity. One of the most widely used indices is the Palmer Drought Index (PDI—[17]), which relates to the humidity balance of the soil (the difference between precipitation and evaporation, accounting also for absorption and runoff) as compared with the *average* conditions in that area. Another index is the "Standardized Precipitation Index" (SPI), which measures the deviation of the actual precipitation from the average (reference) conditions in a given area, measured in units of "standard deviation".

Table 1 [3] defines the drought severity categories and cross-relates them to the possible effects and the values of the indices mentioned above.

The drought definitions in Table 1 are modern and are concerned with drought durations of up to one year only. It is presumed here that the ancient peasants in most areas of the world, being conditioned to hardships of higher severity than the modern farmers, could sustain a single year of D 3 or even a D 4 drought. But often the climatic fluctuations causing the droughts occur in "clusters" [4]. The vulnerability of the ancient peasants to such strings of drought years must have been a function of the drought severity and its length, and of the sensitivity of their agricultural crops and procedures to such variability.

For the sake of this discussion, droughts are defined here based only on rainfall, and not on soil moisture balance.

3. Droughts and the Maya

Even though the Maya were very much concerned with time, numbers, and cycles of the heavenly bodies, and had timed events to the day on a time scale of millennia, there is no indication anywhere in the Maya records relating to drought periodicity. It is possible that there had been records of droughts and their periodicity in the past that had been destroyed by the Spanish Conquistadores. But it is just as probable that there was no such record at all, since no periodicity could be detected.

The detection of droughts' periodicity requires some definition of "a drought" in terms of observable parameters and observations over a very long period of time. The Maya could and did record gross events connected with droughts, such as famines and migrations (see below), but most probably they did not measure rainfall and other such physical parameters of moisture balance in the soil.

It can be asked if sufficient data were accumulated in the combined memory of the people to enable the detection of periodicity or the lack thereof (Mark Brenner, personal communication, 2000)? As is well known, the Maya had a long combined memory (since they had written records) regarding droughts, diseases and other disasters, as exemplified in "The Books of Chilam Balam of Mani" and of other places [5–7]. Another example for the length of Maya memory is found in Diego de Landa's report on the events in the Yucatan ([12] [1978, section X]), where he cites his informers telling him of droughts, diseases, and other mishaps that had occurred 100–150 years earlier. Therefore, if there were any drought cycle within this time scale, it is most probable that they would have recognized it. Gill [7, pp. 306–307] presents a table of historical famines in Yucatan. It includes 27 occurrences over a time period of 400 years. Fifteen out of the 27 occurrences were droughts, of which four are termed "severe". Therefore, in historical times, the average frequency of a drought (that is "worth" mentioning) is one in about 27 years, and the average frequency of the "severe" droughts is one in about 100 years. Assuming similar frequencies of droughts also in the ancient times, Maya peasants with an average life span of 35–40 years, would have encountered 5–10 minor droughts (D 0/D 1) and maybe one severe (D 2/D 3). So that "what if it does not rain sufficiently" must have been a constant concern for them, and the "Big Events" only strengthened these worries (if they survived them …). Therefore, the Maya peasants had devised measures for dealing with such occurrences, such as the use of resilient species of crops, combining several types of crops, land modifications to improve water collection and retention (terraces), family stores, etc. As a result of such actions, not every year with less than average rainfall resulted in a famine on a large scale (though some individual peasant families must have suffered considerably).

Wells, which at present abound in central Yucatan and Belize, are known to have been used also by the ancient Maya [18]. The level of the aquifer is bound to drop significantly with clusters of "lean years", thus at least some of the wells would have dried out, thus hampering the peasants' capabilities of combating drought and famine.

If drought periodicity could be detected it would have helped in taking measures to mitigate its effects. Hence, from the peasant's point of view detecting such periodicity must have been of the utmost importance. If drought periodicity had been detected, it may had served as a tremendous incentive for the invention and development of long-term storage facilities on all levels of society, in spite of the harsh environmental conditions. The fact that such storage facilities have not been found in the archaeological evidence and are not present in the lore of the present-day descendants of the ancient Maya is an indication that no such effort had been made, probably because there was no strong incentive for it, in the form of predictable droughts.

At present we have indications that the occurrence of droughts is not periodic. If we *assume* that droughts *are* random events, test the average frequencies of these random events and find them similar to the frequencies of the real events, then the "randomness" of the real events is somewhat more substantiated and the reason for the lack of long-term storage facilities is made clearer.

This requires a detailed record of the palaeoclimate of the Maya area. Luckily such a record is now available [2].

4. Method

It is attempted here to test whether the assumption that droughts are random events results in realistic *average frequencies* of drought occurrences—or not. The testing is possible since we have the "observed" climatic history of the Northern Yucatan area with sufficient time resolution, extending over several millennia [2].

According to Sharer [19, p. 23], most of the Yucatan peninsula receives an average annual rainfall of between 1000 mm to 2000 mm. The North-East receives less than that and in the extreme North-East, even less than 500 mm. Similar information with minor differences is also given by Hammond [8, chapter 3]. Therefore, a long-term average annual rainfall (P) of 1500 mm is taken as typical for the central lowlands, and a standard deviation (σ) of 400 mm was assumed, so that the approximate total variability ($\pm 2\sigma$) is $\sim 700\text{ mm} < P < \sim 2300\text{ mm}$.

A "lean year" was defined as a year with annual rainfall value below a given threshold P_{th}. Three values

Table 2
The frequencies of the Lean Years strings in 1000 "years" per P_{th} value

P_{th}	Length of Lean Years string						
	1.5	2	2.5	3	3.5	4	>4
1000 mm	–	6	2	3	2	1	–
1100 mm	7	25	6	7	–	–	2
1200 mm	5	36	3	10	1	4	3

were selected for P_{th}, 1000 mm (P=1.2σ); 1100 mm (P=1.0σ); 1200 mm (P=0.75σ). The first is a "harsh" value, meaning that it takes a relatively dry year (in central lowland terms) to be counted as a "lean year". The second value conforms to a "moderate drought" (D 1). The third is a relatively "mild" definition of a "lean year". These definitions relate to the "standard precipitation index" (SPI) of Table 1, so that P_{th}=1000 mm is equal to an SPI of −1.25 (between D 1 and D 2), P_{th}=1100 to SPI of −1.0 (D 1), P_{th}=1200 to SPI of −0.75 (between D 0 and D 1).

A random number generator was run within the rainfall range of variability mentioned above, to get random annual precipitation values. Each run consisted of 100 "years". For each year we tested if the rainfall value was below the threshold value P_{th}. The years with rainfall value below P_{th} were considered "lean years". For each threshold value we ran 10 runs of 100 years each, thus having a "data base" of 1000 "years" for each value of P_{th}, and a total of 3000 "years".

Running the calculation, it turned out that there were quite a few events of strings of consecutive lean years. These strings varied in length, and the longest chain encountered in this study was of 12 "lean years". Additionally, there were quite a few cases of two lean years and in between them one year with a rainfall below average (but above P_{th}). These were defined as 1.5, or 2.5 or 3.5 etc. lean years.

Table 2 gives the number of occurrences of the strings, in 1000 years, for each value of P_{th}, as encountered in this study.

As was mentioned earlier, it is presumed here that, generally, the length of the "Lean Year String" plays a more significant part in the severity of a drought as experienced by the peasants, than the severity of any particular "Lean Year". As we have three different definitions of a "Lean Year", it is obvious that a string of Lean Years based on the P_{th}=1000 mm threshold will have more severe results than a string of the same length based on the P_{th}=1200 mm threshold. Based on this, we created an arbitrary (subjective) table (Table 3) of definitions of drought severity.

Strings shorter than those defined as a severe drought, were considered "to cause difficulties", but not a situation that the average peasant family cannot cope with.

Table 3
Definitions of drought severity in terms of the length of Lean Year strings

P_{th}	Severe	Disaster	Catastrophe
1000 mm	≥2	≥3	≥4
1100 mm	≥2	≥3	>4
1200 mm	≥2.5	≥3.5	>4

Table 4
Drought occurrence in 3000 "years", 1000 "years" per P_{th} value

P_{th}	Severe	Disaster	Catastrophe
1000 mm	34	6	1
1100 mm	40	9	2
1200 mm	21	8	3
Total	95	23	6

Table 4 gives the frequency of "severe droughts", "disasters" and "catastrophes", as encountered for each 1000 years sequence, based on the selected values of the threshold.

5. Results and discussion

From Table 4 it is clear that the frequencies of the various droughts are similar for the various values of P_{th}, which means that the definitions (threshold for a Lean Year; severity of a drought) roughly balance each other.

Therefore, it makes sense to combine these occurrences and average the total results over the total of 3000 years, to get:

Severe drought on average every 32 years
Disaster on average every 130 years
Catastrophe on average every 500 years

The above frequencies were derived assuming the long-term climate is constant on average. It is well known that there is a long-term variability of the climate of any given location. Therefore, since the droughts were defined by the deviation of the rainfall in standardized units relative to the long-term average, these droughts of various severities are superposed on the long-term variability.

There are two different scales of "long term" here. The first—for the derivation of the average rainfall (P) which is of the order of several decades. The second—for the discussion of the general (palaeo) climate variability, which is of the order of millennia so that the first "long term" is superposed on the second one.

Lately, a series of studies has been carried out, delineating the palaeoclimate variability in various

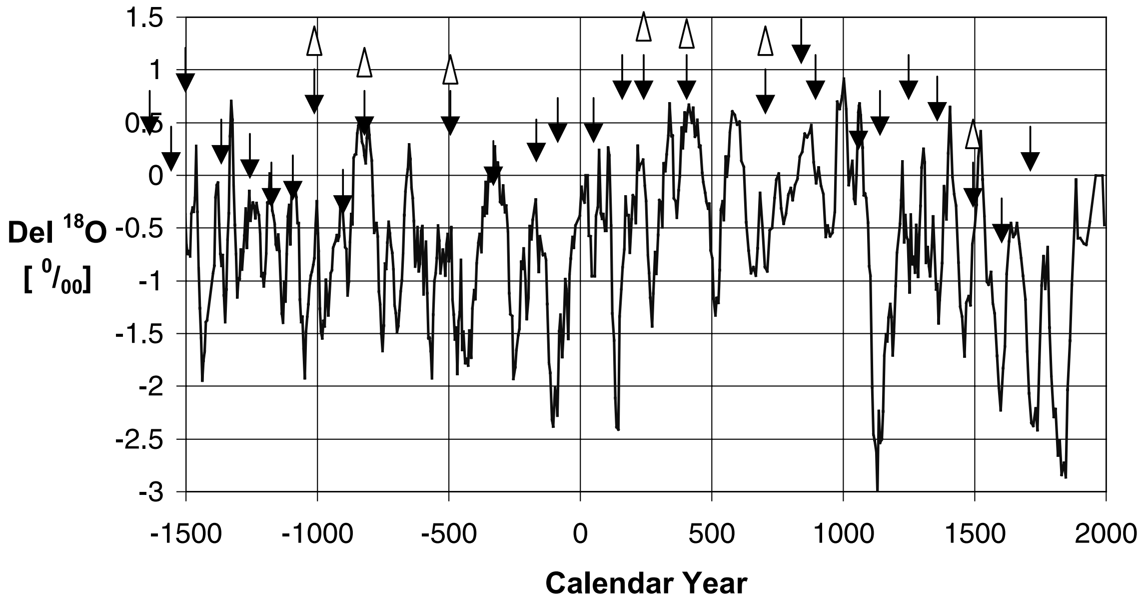

Fig. 1. The variation with time of δ^{18}O in *Pyrgophorus coronatus* as measured in the core taken in lake Punta Laguna, 5 point moving average ([2]. By permission of J.H. Curtis). Arrows mark dry events ("disasters"), triangles mark prolonged dry events ("catastrophes")

locations in the Yucatan. The researchers used several proxies for their studies, including pollen, stable isotope geochemistry, magnetic susceptibility, elemental composition and radiocarbon dating in lake sediments cored in various lakes in the Yucatan.

Pollen diagrams like the one presented by Leyden [13] can give general trends of palaeobotanical history, from which general palaeoclimatic trends can be inferred, but the time resolution is too coarse to detect a single drought or even what we term a "disaster" or a "catastrophe".

The study by Hodell et al. [10] who took cores from lake Chichancanab in northern Yucatan, is much more detailed. The authors use the concentrations of $CaCO_3$, sulphur and δ^{18}O in ostracods and gastropods as indicators of Wet/Dry periods. Their basic resolution is 1 cm in the core, which is equivalent to about 25 years, based on their radiocarbon dating and assuming a constant rate of sedimentation in the lake (which is questionable given the climate variability).

A similar study was carried out by the same team in lake Punta Laguna, with higher time resolution (decadal) due to a higher average rate of sedimentation. The high temporal resolution data, which correlate nicely with Quelccaya ice core data which have a one year resolution, enable the detection of a single dry or wet event of significant duration, i.e. "disasters" and "catastrophes". The data reduction process (5 point moving average) which filters the "noise", coupled with detailed chronology, enables attributing specific dates to specific major events. Dry events, indicated by positive peaks of δ^{18}O are noticeable in their data throughout the recorded period. Some of the peaks are narrow, representing relatively short dry periods. Some of the peaks are wide or have a flat top, indicating prolonged dry periods. It is interesting to note that the "narrow" peaks are more pronounced in the δ^{18}O record of the gastropod *Pyrgophorus coronatus* and the "wide" peaks are more pronounced in the δ^{18}O record of the ostracod *Cytheridella ilosvayi*. Still, most of the "wide" peaks roughly coincide in both records. In their 3500 years record (see Fig. 1) there are 28 significant dry events, i.e. with an *average* period of 125 years. Out of these dry events, there are seven events that are wide (of long duration) and stand out relative to their immediate neighbors (~800 BC; ~600 BC; ~300 BC; ~AD 400; ~AD 600; ~AD 850; ~AD 1700). Some of these catastrophic events are superposed on a dry period extending from ~AD 300 to ~AD 1100, thus shortening the average period. Still, the average period of all these events, over the whole recorded period is ~500 years.

A more recent study by the same team, coring again in lake Chichancnab [11] resulted in an even more detailed sequence of data, this time extending over a 2600 year period, from ~600 BC to the present. In their record of δ^{18}O in the gastropod *Pyrgophorus coronatus* there are 20 significant events of dry periods (noticeable as positive peaks of the δ^{18}O record). For a 2600 year period this yields an average of 130 years between these events. Again, the wider, long duration peaks are not very significant in this record.

Another study of sediments in the Cariaco Basin, off the coast of Venezuela [9] has a sub-decadal time resolution of intermittent terrestrial and marine sedimentation. It yields five peaks of low titanium

(terrestrial element) deposition, indicating a dry climate, over the last 2300 years, i.e. an average interval of 460 years.

Therefore the frequency of the "random" drought, at the different levels seems to be quite realistic.

If we take Gill's data [7, pp. 306–307] as mentioned before and assume that Gill's "drought"="severe drought" in our terms and Gill's "severe drought"= "disaster" in our terms, then these data of 27 and 100 years compare favorably with the model results of 32 and 130 years. The little disagreement of the two sets of results can be attributed to the fact that the actual data set (Gill's) is too short compared to the model. Additionally, because the agricultural crops and procedures have changed significantly since the Spanish conquest, their sensitivity to droughts has changed also, probably in the direction of higher vulnerability, thus possibly turning a "severe drought" into a significant famine.

It is interesting to note in the data of Fig. 1 that around the year AD 1200 there was an exceptionally wet period, lasting for about a hundred years, which marks the beginning of a process of a wetter and wetter climate. According to these data this process lasted until around AD 1850 and it roughly coincides with "The Little Ice Age".

In addition to the lake sediments and the written records, a useful proxy for climate variations is tree-ring analysis. There are detailed dendro-sequences for various regions in the US, but unfortunately we know of none for the Maya region. In the US, tree-ring analysis, together with other proxy data of lower resolution were used to construct the drought history of the Great Plains [23]. Interestingly, they identified 4 "megadroughts" in the last 2000 years in the Great Plains, which fits the present model average frequency of "catastrophes".

The above reasoning does not constitute, in any way, a proof to a cause/effect relationship between catastrophic droughts in Northern Yucatan and the major cultural transitions in the Maya world. This model cannot predict the actual timing of a drought of a given magnitude, in a given area, it can only predict the *average* time between such occurrences.

Nevertheless, the agreement between the measured data and the results of the model is very compelling to support the basic assumption of the model—that for all practical purposes, droughts can be considered random events.

As can be seen in Gill's table [7, pp. 306–307], in de Landa's report ([12] [1978, section X]) and in other sources, droughts caused only about half of the actual famines in the Yucatan and the other causes being at least as random as the droughts. This makes it impossible to predict the occurrence of a famine with any reasonable precision. Most probably this fact has given the High Priests a lot of room for gloomy prophecies that could be revoked only by their tremendous efforts of appeasing the Gods (in case there is no famine) or that the "sins" of the people were so severe that in spite of their efforts the famine could not be prevented. Had there been a recognizable pattern to the droughts' and/or famines' occurrences, the power of the clergy would have been greatly diminished. Hence, the fact that there is no such pattern and droughts could not be predicted, must have "played into the hands" of the clergy, which, in the case of the Maya, were synonymous with the ruling elite, increasing their possibilities of controlling the populace.

However, on the level of the individual Maya peasant, on average each one of them had experienced several "hard times" and one or more "severe droughts". It can be argued that this was a sufficient incentive to develop appropriate means for storage. Apparently it was not. This is in line with the theory presented by Bjorkman [1] of the effect of the "cognitive time" on the actions taken by people. People are less concerned with things that are distant in the past or in the future than they are with the present. The actions taken are biased by present concerns since the past and the future are not fully remembered or correctly anticipated. Therefore, without a clear-cut future prospect (periodicity of droughts) there was no strong motivation for such developments.

Another aspect of the effect of the random nature of droughts is in the Darwinian approach of "natural selection" as discussed by Masden et al. [15]. They claim, based on a simple model, that in an uncertain, fluctuating, environment (i.e. random droughts) the selection favors populations with low fecundity. They also connect low fecundity with cultural elaboration, hence the more elaborate, the Elite, have better chances of survival—on average. It is not clear over what length of a period the average has to be taken for the process of selection to be noticeable. We suspect that this period has to be at least several centuries long. However, in cases of severe events like a "catastrophe", a "megadrought" or (on a different vain) the Holocaust of World War II or of Rwanda, cultural elaboration does not improve anybody's chances of survival. On the contrary, the culturally elaborate have basically lower fitness for survival under such harsh conditions. Additionally, as it turns out the average period between catastrophes is on the same time frame as that of the selection. Therefore, such events may totally mask the buildup of the average process of selection.

Although the method described here was applied to the Maya countries, it was not derived with a specific location in mind. The model can be applied to any specific climatic region in the world, based on the local average rainfall and its variability, and the sensitivity of the local agriculture to this variability. This can be done

by the use of available information on the local rainfall and its variability and assessing what constitutes a "disaster" and a "catastrophe" for the local population in terms of extended periods of rainfall deficiency. When the threshold for a "lean year" is clear there is no need to test several thresholds. This was done in the present work only in order to test the sensitivity of the method. If similar results are found, then the randomness of drought occurrence may have had similar effects on the relationships between clergy and populace.

The method described here is not relevant to cultures like those in the Nile valley or in the river basins of Mesopotamia, where the local rainfall has almost nothing to do with the local agriculture. In addition, in those places long-term storage of food products and water was not as big an issue as it was with the Maya, due to their dry local climates and the (more or less) reliable supply of water.

6. Summary and conclusions

The random occurrence of droughts in any given climatic region was simulated using a random number generator and was tested against data from the Maya world. It was found that strings of "Lean Years" occurred frequently, creating a "Severe Drought", a "Disaster", or a "Catastrophe", depending on the length of the string. It was also found that severe droughts occur approximately every 32 years, a disaster approximately every 130 years, and a catastrophe approximately every 500 years. These last two values are very close to those observed experimentally in lake cores and to the historical records, thus suggesting that droughts can be considered random events.

While there exists a strong agreement between the model data and the measured data, droughts are considered by the meteorological community as occurrences that can be predicted. However, as stated above, given the inability to account for all the factors required for the predictions it seems that droughts will continue to be perceived as random occurrences for a long time to come.

The model developed here is not restricted to a specific area. It can be applied to almost any location, provided the climatic conditions and variability, and the sensitivity of the agricultural crops and procedures to this variability are known or can be estimated.

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